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A study of the use of solar concentrating plants for the atmospheric water vapour extraction from ambient air in the Middle East and Northern Africa region

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Abstract

In this paper an insight of two different methods for the production of fresh water is given within the framework of the FP6 project "AQUASOLIS" aimed at exploring the use of solar concentrating plants in Mediterranean countries for the supply of renewable water. The method presented in this paper is the extraction of water from air by direct cooling of humid air below the dew point. The energy consumption of the system is calculated and the possibility to use the solar cooling system for supplying the required refrigerating power is explored. Quantitative calculations are carried out simulating different weather scenarios in the three target Mediterranean partner countries: Jordan, Lebanon, and Morocco.

Keywords: Atmospheric water vapour processing; Extraction of water from air; Middle East; Northern Africa

1. Introduction

Water scarcity is an acknowledged problem for the development of a vast amount of the world population in the regions of Northern Africa, Middle East and Central and Southern Asia. While the absence of an easy access to energy supply may severe the potential of economical and technological progress of a population, the impossibility to access easy and affordable sources of fresh water is a matter of survival.

The development of economically and environmentally sustainable technologies for the production of fresh water for drinking and for agricultural use has been promoted at international and European level. The "Plan of Implementation of the World Summit on Sustainable Development" states that population access to drinking

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water, the development of new water production technologies and the change in the natural resource exploitation models and in the development patterns are vital issues that must be addressed by the governments of all countries.

At the European level the production of drinking water and the reuse and treatment of waste water by means of environmental friendly technology is pointed out both in “The EU Water Initiative” [1] and “The EU commitment towards the Millennium Development Goals” [2] in particular where access to drinking water is acknowledged as a key step to eradicate extreme poverty and hunger and to ensure environmental sustainability to the future of humanity.

Even though a major step forward in the availability of water can be made on the demand side by reducing water consumption in the industrialised countries and improving the efficiency of the distribution networks in the developing countries, technological progress must be focused mainly on the improvement of the supply side of the system. This improvement can only be based on renewable energy sources. Whereas the traditional approach for desalination has been on using photovoltaic power, recently the development of solar concentration plants has opened up the possibility of using these plants as the energy sources for this purpose. This idea has led to the “AQUASOLIS” fp6 project sponsored by the European Commission which had the purpose of exploring this field, in particular within the area covered by the larger fp6 REACt project which is aimed at the actual setup of solar concentrating plants using linear parabolic collectors for the production of heating and cooling for buildings. The present paper summarizes the results of an assessment of the energy balance of some of the approaches to the use of concentrated solar power for fresh water production. A complete assessment will be made available in the final AQUASOLIS report [3].

Desalination can be regarded as the method based on the most mature technologies and an excellent way to exploit a potentially undepletable source of water like the sea. The price of desalination is the energy required to remove the salt from seawater making it usable for nutritional and sanitary uses. The energy used can be mechanical, thermal or electrical or a mix of the three and is provided usually by fossil fuel combustion based technologies. The focus of research in desalination is moving towards small scale plants that can be partially or completely powered by renewable energy. In this field the main role is played by photovoltaic powered reverse osmosis. The system however is expensive owing to the low conversion factor of the photovoltaic system and the high cost of the cells. Where wind power is available the efficiency can be highly improved and reverse osmosis can be regarded as one of the most promising technologies. Yet, the maintenance of the ion exchange membrane remains a major issue in remote areas of low technology countries.

Many other technologies using solar thermal power for the distillation of the water content of seawater are being considered in order to provide a feasible solution for decentralised solar based water production. In this field desalination by humidification and de-humidification of air is giving promising results. Major improvements must be made nevertheless to overcome the low efficiency of solar based systems. A large, clean and renewable source of water is atmospheric air. The water content in the atmosphere is estimated to be 14,000 cubic kilometres, whereas the amount of fresh water in the earth is only about 1200 cubic kilometres [4]. Each cubic metre of air throughout earth’s 100–600 m thick atmospheric boundary layer contains 4 to 25 g water vapour, potentially allowing water supply almost anywhere. This potential may be practically exploited in a renewable way by using appropriate technologies.

In the following we will examine the use of a system is based on the REACt cylindrical solar concentrating system [5] that uses absorption chillers as a source of cooling that is used from condensing water from the air. This is only one of the possible uses of concentrating power provided by such plants. The heat provided at $T >$ than ca. 150 could be used for the distillation of brackish water or seawater; a possibility that is alternative to reverse osmosis and especially interesting when the salt concentration is too high for the use of conventional membranes. The chillers could also be replaced by systems based on absorption/desorption of water from hygroscopic salts such as $CaCl_2$. In the present paper, however, we will examine more in depth the approach based on water condensation from the air utilizing conventional chillers.

2. The system for direct extraction of air

The system under study in this paper is based on the extraction of atmospheric water by cooling of moist air below the dew point. This system is base on a solar concentrating system which operates a conventional ammonia or LiBr chiller that produces a cooling effect which is used for the condensation of water from the atmosphere. A block diagram of the system is presented in Fig. 1 with a special focus on the energetic contribution involved. The parameters taking into account energy and water collection efficiency are also pointed out.

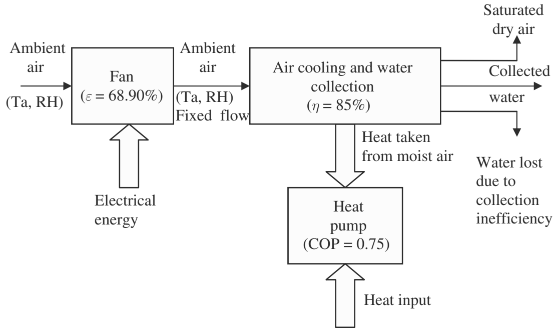

Fig. 1. Schematic description of the system.

The system consists of a fan that can be fed by electrical energy (ideally coming from PV). The task of the fan is to fix the volume flow of air on the surface of the heat exchanger. The value of the fixed air flow is calculated taking into account the minimum output of water in terms of litres per hour and the minimum value of the relative humidity for the selected location. In these simulations the value of the moist air flow has been fixed to 8000 m^3/h. The efficiency of the fan is given by the sum of three contributions: intrinsic fan efficiency, belt efficiency, motor efficiency. It is very important to maximise the efficiency of the fan system because it is responsible of a high fraction of the overall energy cost of the produced water, since it requires electricity. After the fan, a heat exchanger performs both the cooling and, in its final stages the collection of water that will accumulate on the heat exchange surface and fall to the collection system. Choosing the right configuration of the heat exchanger and collector system is very important since it affects the overall efficiency of the system in two ways: energy efficiency strongly depends from the heat transfer coefficient and the water output is directly proportional to the efficiency in the collection of droplets.

The refrigerating power is fed to the heat exchanger by an absorption chiller of the ammonia/water type. This machine is powered by the heat coming from a parabolic trough concentrating solar collector. The solar part of the system providing the refrigerating power is not directly considered in this study and the chiller is described as a standard heat pump with a specified COP and fixing the cold part of the heat exchanger to a certain temperature ($T = 12$°C in the simulations).

3. Meteorological data

The input data used for the simulation were the meteorological data collected on an hourly basis for the eight location selected in the three

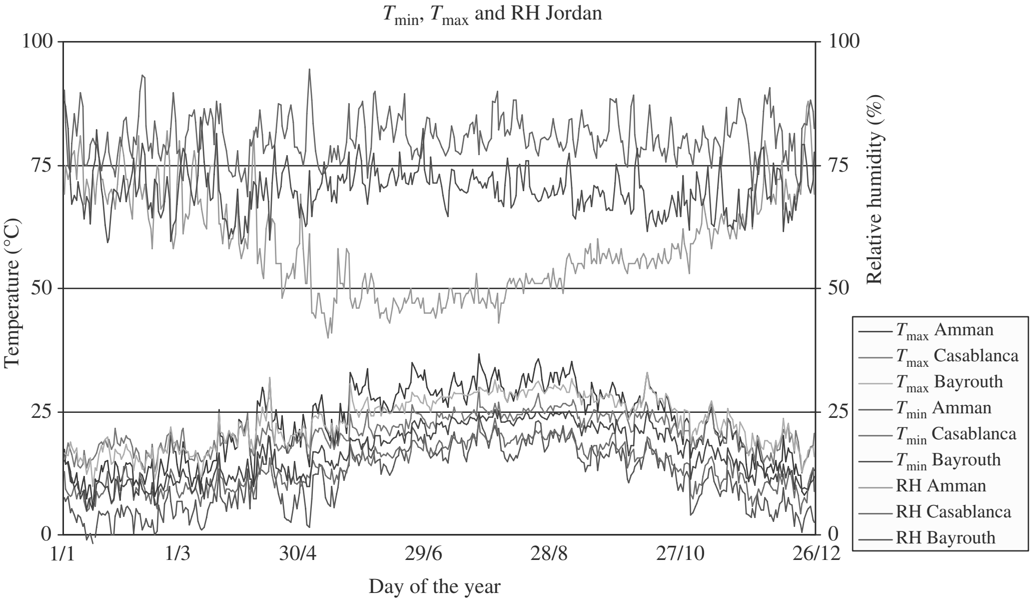

Fig. 2. Meteorological data resume for three of the seven locations: Amman, Casablanca, and Bayrouth.

target countries. Namely, the data used for the simulation were: solar global radiation, ambient temperature and relative humidity. From these three parameters all the thermodynamical properties of moist air can be calculated (see section 4). The locations were chosen in the three target countries of the study: Lebanon, Jordan and Morocco. For each one a minimum of two and a maximum of three locations were selected.

In Table 1 the locations are presented together with their land coordinates.

In Fig. 2 daily mean values of minimum and maximum temperature and mean relative humidity are sketched for three sample locations, one for each country: Bayrouth, Amman and Casablanca.

These data provide insight on the seasonal behaviour of relative humidity. In locations near the sea the relative humidity does not show important seasonal fluctuations, whereas in the interior relative humidity peaks in winter, when the temperatures are lower. This fact accounts for a potential inferior water production in

Table 1

Name of the Location	Country	Latitude	Longitude	Altitude	Sea
Bayrouth	Lebanon	33°N	35°E	18 m	Yes
Tripoli	Lebanon	34°N	35°E	0 m	Yes
Rayack	Lebanon	33°N	36°E	927 m	No
Amman	Jordan	31°N	35°E	19 m	No
Irbid	Jordan	32°N	35°E	566 m	No
Casablanca	Morocco	33°N	7°W	0 m	Yes
Beni-Mellal	Morocco	32°N	6°W	468 m	No

inland locations: when temperature is higher more refrigerating power is needed to cool down the air, while the lower relative humidity means a lower water content (at the same temperature) and consequently a lower water production.

Another important parameter that is reflected in the calculation is the offset between the hours of maximum solar irradiation and maximum relative humidity. The larger the distance between these two peaks, the lower the water production and the higher the need for storage of the cooling produced by the absorption chiller that, in its solar configuration can work only in the hour when there is sun.

4. Simulation and results

From the hourly data of ambient temperature, relative humidity and pressure all the thermodynamical properties of the water–air mix have been calculated thanks to a psychrometric functions library. In the following list the starting data of the simulations are shown. All these functions have been calculated from the ambient temperature, the relative humidity and the atmospheric pressure.

- h_{air}: enthalpy of the moist air [kJ per kg of dry air]
- x: water content, absolute humidity [g of water per kg of dry air]
- h_{dew}: enthalpy at dew point [kJ per kg of dry air]
- ρ_{air}: moist air density [kg of moist air/cubic meter of moist air]
- ρ_{dry}: dry air density [kg of dry air/cubic meter of dry air]

From the set point fixed by the cold side of the heat exchanger (T_{final} = 12°C, $RH_{final} = 1$) the values of these thermodynamical properties at the final point of the process have been calculated. For each value the difference between the starting value (calculated from the meteorological data) and the arrival values (calculated from the arrival set points) gives:

- the potential quantity of water that can be extracted per kilogram of dry air
- the quantity of enthalpy that has to be extracted per kilogram of dry air.

As already mentioned, the air volume flow has been fixed to a value of 8000 m^3/h for all the locations. From the moist air flow a value of the dry air flow can be calculated. The dry air flow will vary from hour to hour accordingly to the water content of water and the density of moist and dry air. From the dry air flow through the fan a value of the water that can be extracted in an hour can be calculated multiplying the difference in absolute humidity times the dry air flow.

The thermal energy cost is calculated in the same way, only substituting the difference of enthalpy between the starting and final point and multiplying it times the dry air flow. The electrical energy consumption of the fan has been calculated dividing ideal power (the pressure drop times the volume flow) of the fan by the energy efficiency of the fan, that has been taken of a 68.90% value, in order to properly account for the three main cause of inefficiency:

- the efficiency of electrical motor (0.88)
- the efficiency of belt transmission to the shaft of the fan (0.87)
- the efficiency of the mechanical system of the fan (0.9).

The values calculated from the difference of water content and enthalpy have been divided by two efficiency terms:

- the COP of the heat pump (0.75%);
- the water collection efficiency, assumed to be 85%.

The yearly values of heat and electrical energy consumption, total energy consumption, water production and specific energy per cubic

Table 2

Location	Thermal energy for the chiller (kW h/year)	Electric energy for the fan (kW h/year)	Electricity/heat fraction (%)	Total energy consumption (kW h/year)	Water production (m^3/year)	Specific energy (kW h/m^3)
Bayrouth	167893.82	9019.73	5.1	176913.55	69.2	2556.46
Tripoli	182070.36	9003.79	4.7	191074.15	84.7	2256.54
Rayack	37531.42	3053.12	7.5	40584.54	5.1	7910.04
Amman	93423.66	6636.49	6.6	100060.15	20.7	4826.71
Irbid	113231.56	7336.24	6.1	120567.80	32.4	3724.23
Casablanca	131574.83	9577.69	6.8	141152.52	56.77	2486.55
Beni-Mellal	101852.73	6243.95	5.8	108096.68	21.82	4953.36

meter are reported in Table 2 as resulting from the simulation.

From this table it is apparent that both the quantity of water produced and the specific energy consumption are more favourable in locations near the sea (Bayrouth, Tripoli, Casablanca) or in Irbid, an inland location but with high relative humidity throughout the year. In the three sea locations the specific energy figure is four times bigger than the theoretical figure of 680 kW h/m^3 that is the latent heat of vaporisation and is stated as a theoretical minimum in some literature [6]. In Figs. 3–5 the data on water production, specific energy and total energy consumption are presented on a monthly time scale.

5. Assessment and future research

The results of the calculations presented here point out a strong dependence of water production on season. This explained by the higher

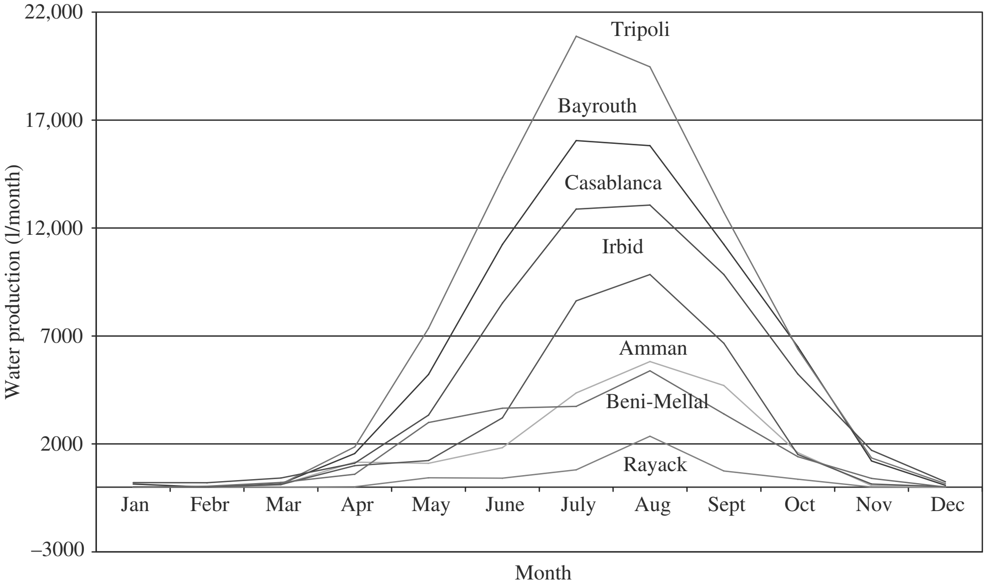

Fig. 3. Monthly distribution of water production.

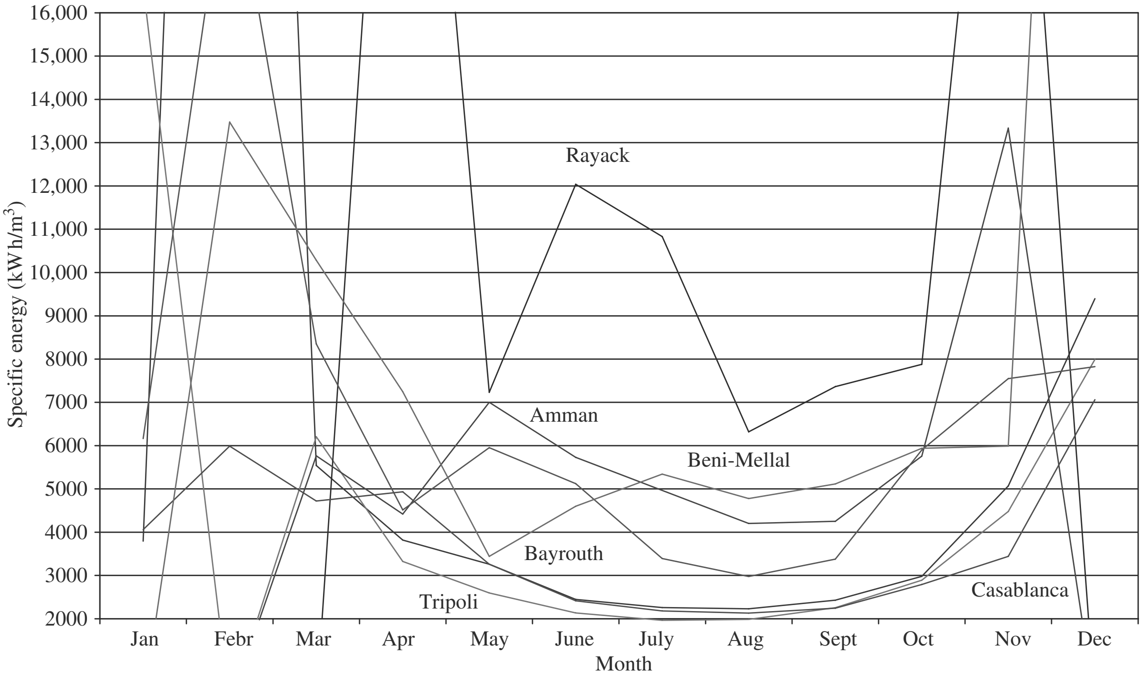

Fig. 4. Monthly values of specific energy.

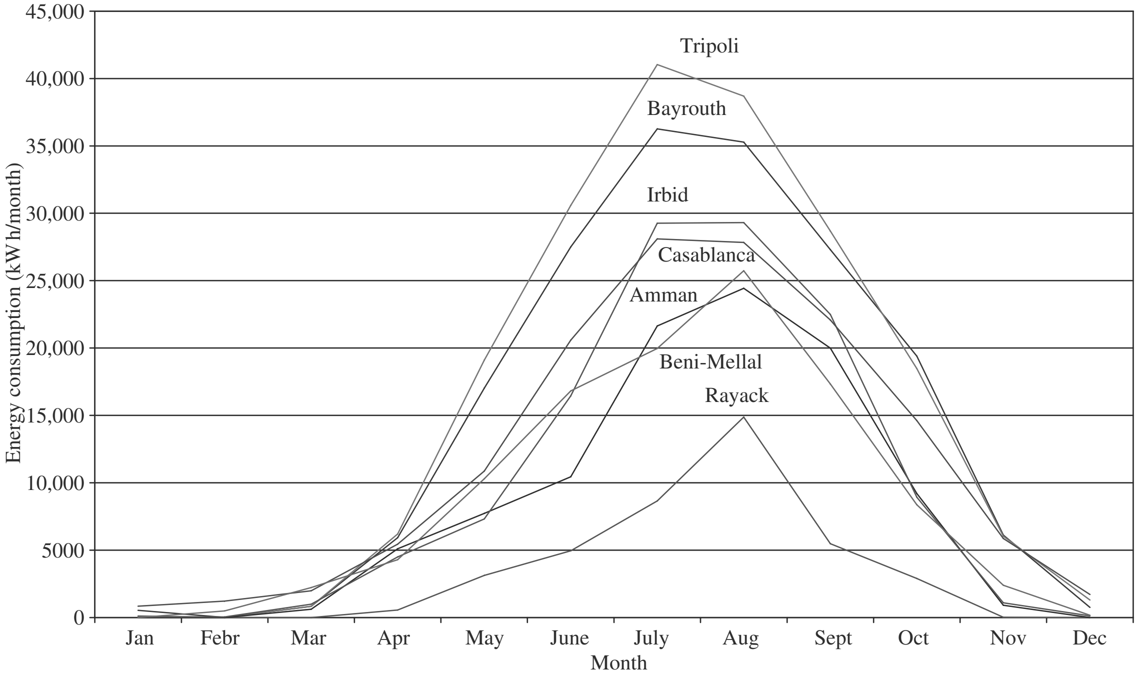

Fig. 5. Monthly distribution of energy consumption.

solar radiation and the number of sunny hours during the day in that period. The energy consumption consumed for extraction is high compared to other, conventional methods of fresh water production such as reverse osmosis. An improvement to lower down heat consumption is the use of pumped sea water as a refrigerant. In this respect, data on the temperature of sea as it varies with depth must be collected in order to estimate the additional energy required for pumping. In this sight also sea water reverse osmosis powered by PV cannot be overlooked as a potentially competitive alternative. Moreover, alternative solutions still based on solar concentrating plants but based on different approaches will be analysed in the future and the result will be compared with the ones presented here:

- Extraction of water from air using a liquid desiccant ($CaCl_2$): the presence of the desiccant enhance water extraction and in principle requires less energy consumption. The kinetic of water absorption desorption must be studied in order to verify the potential water production of the system during time.
- Solar pumping of underground water: this analysis requires information of the depth of underground water and has the disadvantage of using a potentially depletable source.
- Sea water desalination using solar distillation or a humidification dehumidification technology.

However, even the simple approach considered here, the direct use of the cooling power provided by chillers to extract water from air can be considered as economically interesting in specific conditions. If the plant is used in a multiple mode for the production of sanitary hot water and air conditioned, then the energy used for the production of fresh water can be considered essentially at “zero cost.” Therefore, the approach considered here may be convenient areas where alternative technologies are not available or not feasible.

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